

# **Enhanced Predictability Through Lagrangian Observations and Analysis**

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## **LONG-TERM GOALS**

Our long-term goal is better understanding of mesoscale and submesoscale ocean dynamics and their influence on transport processes. We are now focused on applying Lagrangian observations and analysis tools to ocean model velocities to:

- Predict the evolving path of sensor arrays.
- Evaluate the accuracy of Lagrangian predictions.
- Use errors in Lagrangian predictions to provide feedback to the modelers on ways to improve model dynamics from the Lagrangian perspective.

## **OBJECTIVES**

Our original proposed work statement focused on applying stochastic ensembles to both HF radar archives in Monterey Bay and model archives in the Gulf of Mexico to characterize the influence of subgrid scale processes on Lagrangian structures like manifolds or synoptic Lagrangian maps. Over the past two years, emerging Navy operational needs for accurate Lagrangian forecasts have shifted our priorities to analysis of the East Asia Seas region, where real-time forecasts from an operational Navy data-assimilating model (EAS-16) and a number of at-sea experiments that include drifter deployments provide a unique opportunity to both develop Lagrangian analysis predictions in near-real time and to evaluate the quality of these predictions using independent observations. As a result of this shift in our focus, these five objectives were pursued during this performance period:

- Provide near real-time Lagrangian analysis support for the LWAD-07-2 at-sea experiment in October 2007, using short-term forecasts from the Navy EAS-16 model.
- Explore the near-surface Lagrangian dispersion characteristics of the EAS-16 model, which includes a number of distinct dynamical regimes, including the Kuroshio and an energetic mesoscale field.
- Compute estimates of decorrelation time and space scales for the EAS-16 model.

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- Determine whether ensembles of random perturbations of EAS-16 near-surface velocities significantly impact the accuracy of trajectory predictions when compared with observed trajectories.
- Explore the climatology of Lagrangian structures (stagnation point distributions and relative dispersion) in the EAS-16 model.

## APPROACH

Publications and previous ONR reports describe a number of Lagrangian analysis tools that we have developed and applied to archives of observed and modeled ocean velocities. Since our analysis methods do not explicitly parameterize subgrid scale processes, our model trajectories describe only simple passive particle advection. Our Lagrangian tools include the following:

- Inflowing/outflowing manifolds
- Gridded trajectories
- Relative dispersion
- Finite-scale and direct Lyapunov exponents
- Synoptic Lagrangian maps, including maps of residence time and domain entrance and exit locations

During this performance period, we focused on Lagrangian analysis of a Navy operational data-assimilating model (EAS-16) for the East Asia Seas region. An at-sea experiment in October 2007 (LWAD-07-2) included the deployment of thirty near-surface drifters, providing an opportunity to validate model trajectory predictions. Work on a related project (*N00014-07-1-0730*, discussed below) provides detailed comparisons between model predicted trajectories and these observations.

## WORK COMPLETED

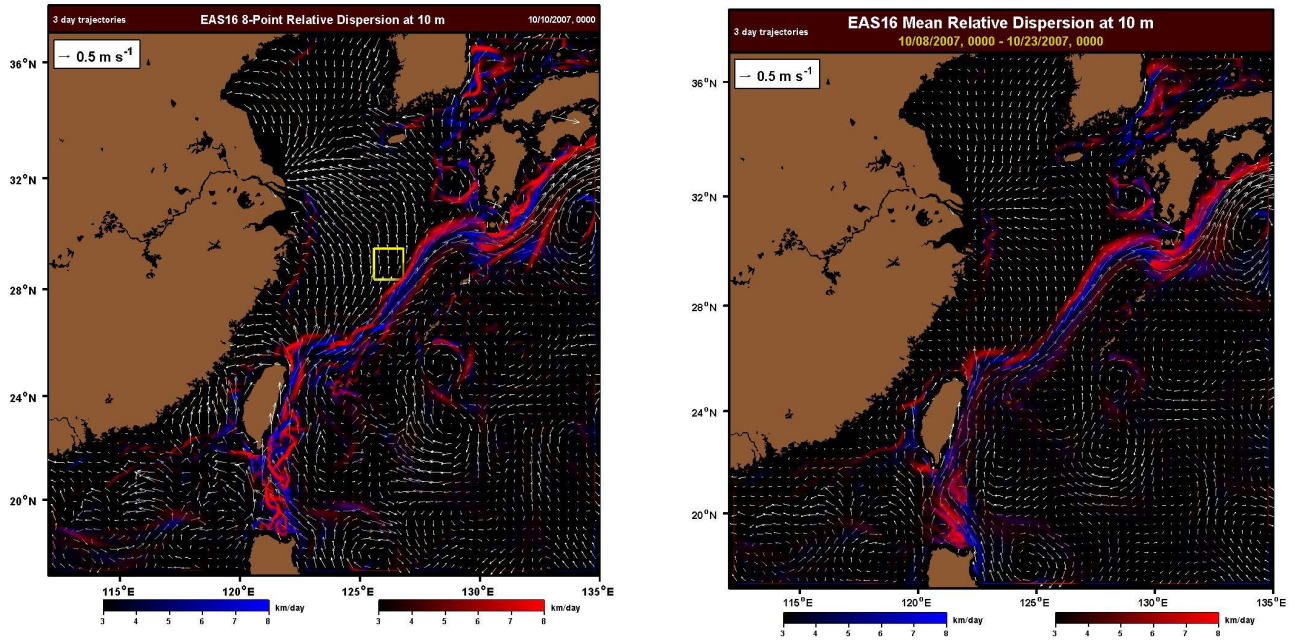
These tasks were accomplished during the performance period:

- To support the LWAD-07-2 experiment, analysis products, including predicted model near-surface mean currents and predicted relative dispersion, were provided to the shore support staff (via the world-wide web) and to the at-sea test coordinators (via ftp link) daily for the period 1-18 October 2007.
- Maps of relative dispersion were computed using both hindcast and forecast EAS-16 model velocities. Matlab code for computing direct Lyapunov exponents (provided by A. C. Poje, College of Staten Island) using the algorithm described by Haller (2001) was also implemented and compared with relative dispersion estimates. The two methods yield virtually indistinguishable results for trajectories computed over periods of several days, as is done here.
- Maps showing the instantaneous distribution of stagnation points were computed from EAS-16 velocities.
- Maps of decorrelation times and spatial correlations were computed for EAS-16 u and v velocity components.

- For thirty SVP drifters launched as part of LWAD-07-2, ensembles of model predicted trajectories were assembled by randomly perturbing EAS-16 hindcast velocities with perturbation magnitudes as large as  $20 \text{ cm s}^{-1}$ . Ensemble trajectory groups were compared with observed drifters to determine whether these random perturbations impact the model's Lagrangian predictive skill.
- The climatology of Lagrangian flow features for EAS-16 velocities was examined using maps of mean relative dispersion and spatial histograms of stagnation point distributions.

## RESULTS

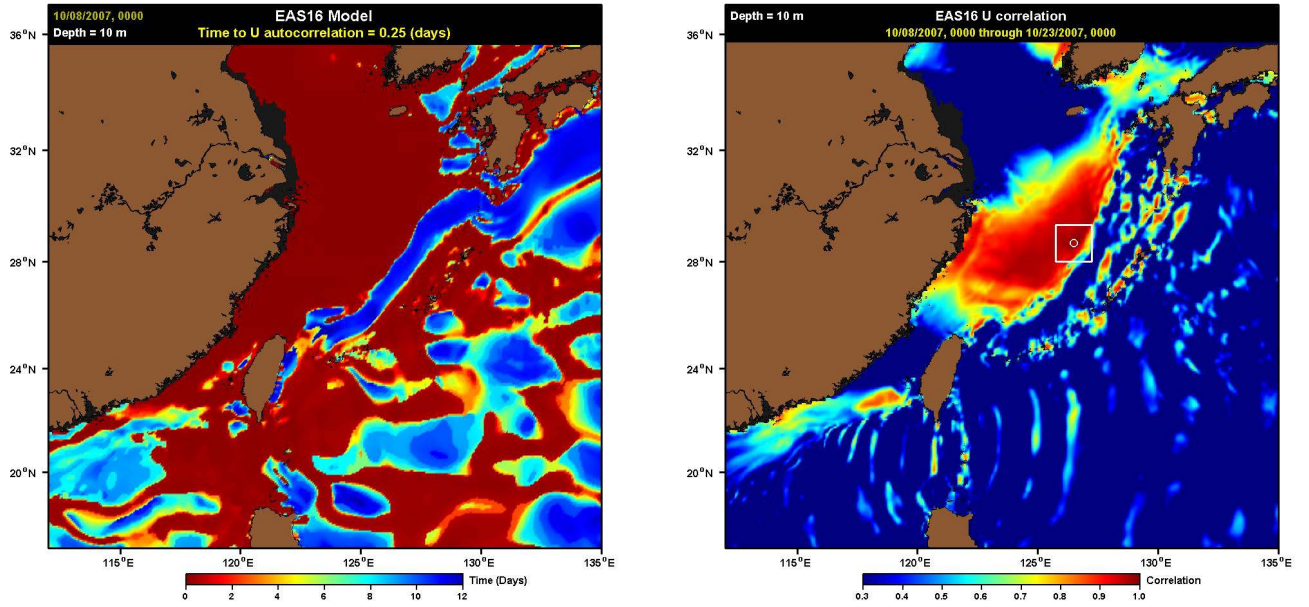
In support of the LWAD-07-2 experiment, a web site was set up at the University of Delaware to provide daily analysis products using EAS-16 forecasts to the shore support team. These products were also passed to the at-sea test coordinators using an ftp link. This effort involved close coordination with the Navy EAS-16 model group at NRL Stennis and with the LWAD-07-2 test group at Johns Hopkins APL. See <http://laplace.cms.udel.edu/~brucel/lwad07> for example products for 17 October 2007. Twenty-four hour mean forecast near-surface currents and relative dispersion forecasts were provided to aid with acoustic sensor deployment decisions. Observed trajectories from thirty SVP drifters launched during the experiment were also provided as the data became available.



**Figure 1:** Maps of relative dispersion (in km/day) at 10m for the EAS-16 model. The left panel shows relative dispersion for particles launched at 0000 UT, 10 October 2007. The right panel shows the mean of daily relative dispersion maps computed for the period 8-23 October 2007. The LWAD-07-2 test area is shown as a yellow box at left.

Preparations for the LWAD-07-2 experiment motivated us to examine the near-surface dispersion characteristics of the EAS-16 model circulation. The EAS-16 domain includes a number of distinct dynamical regimes, including the Kuroshio, a broad shallow shelf northwest of the Kuroshio where

flows are typically weak, and an energetic mesoscale flow region southeast of the Kuroshio. Figure 1 shows example relative dispersion maps for the EAS-16 circulation at 10 meters. In Figure 1, red curves show regions of high dispersion in forward time, while blue curves show high dispersion in backward time. For broad jet features like the Kuroshio, forward and backward dispersion curves typically run parallel. For multipole eddies, peripheral dispersion curves most often intersect where a hyperbolic point (associated with strong deformation) may exist. The left panel of Figure 1 shows relative dispersion for particles launched at each model grid point at 0000 UT on 10 October 2007. The right panel shows the mean of all daily relative dispersion maps computed over the fifteen day interval 8-23 October 2007. Comparison of the two maps in Figure 1 shows that dispersion structure associated with persistent features like the Kuroshio remain quite stationary, while the dispersion signatures of advecting mesoscale eddies southeast of the Kuroshio tends to dissipate with temporal averaging at these time scales.



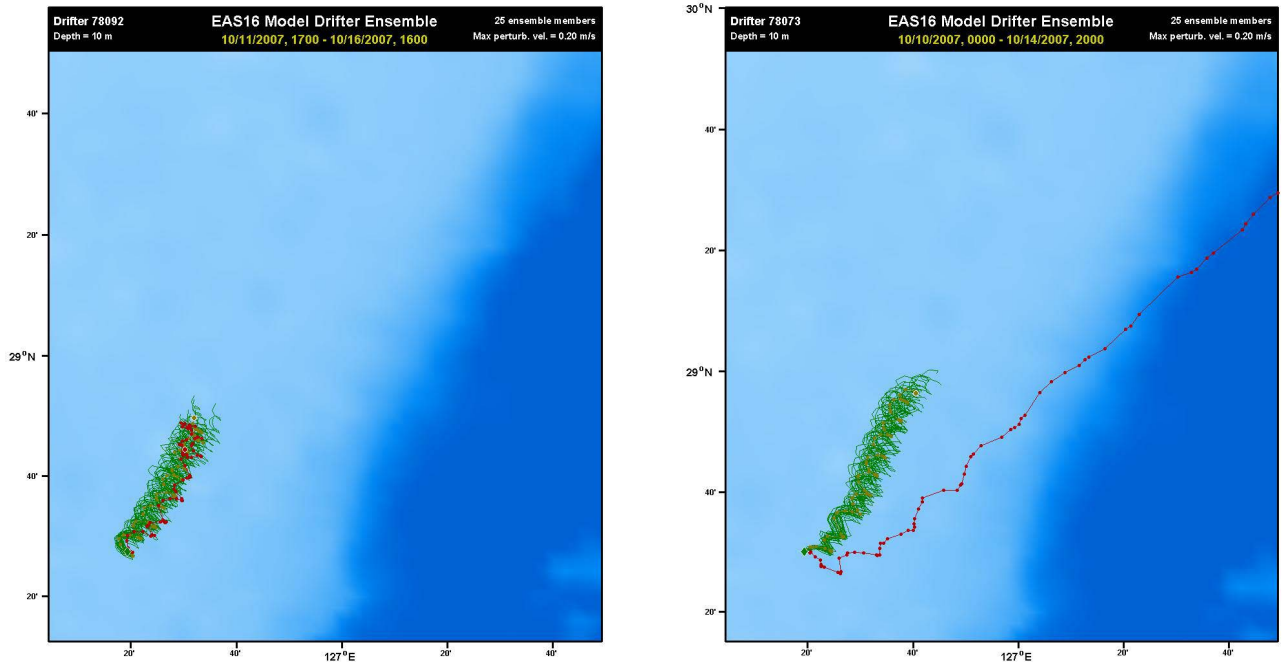
**Figure 2: Time and space correlation maps for the EAS-16 model east-west velocity component at 10m. Left panel shows time required for  $u$  autocorrelation to decrease to 0.25, beginning on 8 October 2007. Right panel shows correlation of  $u$  time series at each model grid point with the  $u$  time series at the center of the LWAD-07-2 test area (shown as white box) for the period 8-23 October 2007.**

Interpreting Lagrangian flow features requires some knowledge of the relevant time and space scales for the flow. For the EAS-16 model, we estimated decorrelation times by computing the time required for the autocorrelation of each velocity component time series at each grid point to decrease to 0.25. A map of this time value for the  $u$  velocity component beginning on 0000 UT, 8 October 2007 is shown in Figure 2 (left panel). Autodecorrelation times can be as large as ten days or more for persistent mesoscale features like the Kuroshio or large eddies. No persistent features are apparent on the shelf region northwest of the Kuroshio. We estimated spatial decorrelation length scales by correlating velocity time series at one location with all model grid points. Figure 2 (right panel) shows one example for the  $u$  velocity component for 8-23 October 2007 using the center of the LWAD-07-2 test area as a reference location. This spatial correlation map shows a broad region of high correlation extending over much of the shelf region northwest of the Kuroshio. It's not clear whether this is



physically plausible. Also note that within the LWAD-07-2 test area (shown as a white box) spatial correlations vary dramatically due to the proximity of the Kuroshio. As expected, this was a challenging location to conduct acoustic experiments.

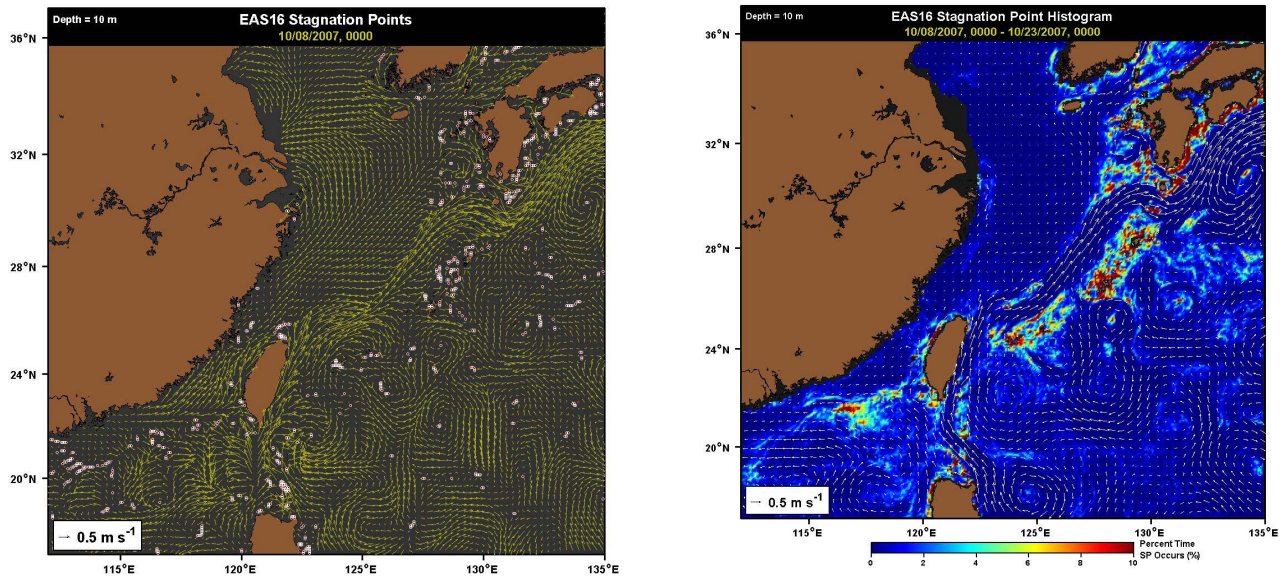
Our experience with work on a related project (*N00014-07-1-0730*, discussed below) shows that EAS-16 model predicted trajectories typically diverge from observations by 15 km or more over periods of 1-2 days. Here, we investigated whether random perturbations of EAS-16 velocities with perturbation amplitudes up to  $20 \text{ cm s}^{-1}$  might account for trajectory separations over these time scales. Figure 3 shows two examples of observed trajectories from the LWAD-07-2 experiment and an ensemble of 25 model trajectories for each case. These examples show two extreme cases of good and bad trajectory agreement. Both cases show that model trajectory predictions are relatively insensitive to random perturbations of this magnitude, so that a more systematic bias or error is likely responsible for the lack of model predictive skill.



**Figure 3: Two examples showing observed drifters (red) unperturbed model drifters (gold) and 25 ensemble trajectories (green) from random perturbations of the model velocities (with perturbation magnitudes up to  $20 \text{ cm s}^{-1}$ ) during the period 10-16 October 2007.**

Stagnation points (where local flow goes to zero) are one indicator of local changes in flow character and can be associated with Lagrangian structures like hyperbolic points that drive significant flow deformation. Consequently, these points are of potential interest to fleet operators interested in maintaining the spatial integrity of an evolving acoustic sensor array. Figure 4 (left panel) shows a map of the instantaneous stagnation point distribution for the EAS-16 model at 10m on 0000 UT, 8 October 2007. Hundreds of stagnation points are evident, concentrated near island boundaries. Some of these points exist near obvious eddy centers. Time series of stagnation point maps show that many of these points are short-lived. To emphasize the persistent stagnation structures, we examined the “climatology” of stagnation points using spatial histograms of stagnation point distributions from hourly model velocities over periods of several weeks. Figure 4 (right panel) shows a spatial

histogram for stagnation points during the period 8-23 October 2007. Again, many stagnation points are clustered near island boundaries. However, in the deep ocean regions, tracks of advecting stagnation regions, some associated with eddy centers are apparent. We are still investigating whether information contained in these spatial histograms may prove useful for fleet operators.



**Figure 4:** *Maps of instantaneous stagnation point locations for 0000 UT, 8 October 2007 (left) and frequency of stagnation point occurrence for the period 8-23 October 2007 (right) for the EAS-16 model at 10m.*

## IMPACT/APPLICATIONS

As part of this effort, and in conjunction with a related project (*N00173-08-1-G009*, see below), we are working with the NRL ocean modeling group to demonstrate how Lagrangian analysis products like relative dispersion maps, developed from short-term model predictions, can be computed at an operational Navy analysis center and provided to fleet operators to support real-time tactical decision making. This demonstration involves porting our analysis codes (both Fortran and Matlab) to Navy computer centers, training fleet operators on their use, and transmitting analysis products to fleet units.

## RELATED PROJECTS

The investigators for this effort are also the principal investigators on two other efforts which are closely related to this work:

*N00014-07-1-0730: Enhanced ocean predictability through optimal observing strategies* – This effort emphasizes detailed comparisons between observed drifter trajectories and predicted trajectories from Navy ocean model velocities. The goal is to quantify the accuracy of Navy model Lagrangian predictions and to provide feedback to the modelers on how these predictions might be improved.

*N00173-08-1-G009: Prediction of evolving acoustic sensor arrays* – This effort is focused on demonstrating how Lagrangian analysis of Navy ocean model predictions can be performed at a Navy

operational center and how Lagrangian products can be delivered to fleet operators on scene in near-real time to support tactical decision making.

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